Journal of Alloys and Compounds 506 (2010) 761–765

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Friction welding of titanium–tungsten pseudoalloy joints

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ARTICLE INFO

Article history:
Received 10 May 2010
Received in revised form 6 July 2010
Accepted 7 July 2010
Available online 15 July 2010

Keywords:
Tungsten pseudoalloy D18
Friction welding
Titanium

ABSTRACT

The friction welding of a dissimilar-metal joint in titanium and tungsten pseudoalloy, in which sintered tungsten grains and alloy Ni–Fe formed respectively the matrix (W-95 wt.%) and the bonding phase, was investigated. The aim of the investigations was to determine which microstructures occur in the titanium–tungsten pseudoalloy joint and which interlayers ensure that there are no brittle structures in it. The friction welding process was found to proceed differently than in the case of titanium–tungsten joints. Stable Ti–Fe–Ni–W intermetallic phases with cracks propagating in them would occur in the joint zone. Proper interlayer of copper on the tungsten pseudoalloy side and vanadium on the titanium side were selected. Joints with tensile strength of 410 MPa were obtained.

1. Introduction

The continuing development of technology calls for application of new materials capable of bearing heavier loads. To this group of particularly interesting materials belong, among others, the metals of groups IV, V and VI of the periodic table, especially titanium, vanadium, zirconium, niobium, molybdenum, as well as tantalum and tungsten. Metals such as these, as well as their alloys, must be protected at elevated temperatures from the effects of oxygen, nitrogen and hydrogen. The generally recommended technique for joining these metals is diffusion welding, which, however, is a laborious and time-consuming process. For this reason, it is of interest, from both the innovative and practical points of view, to investigate the possibility of using friction welding to join such materials [1–3]. Although the friction welding of mono- and multimetallic combinations, exhibiting either perfect or limited solubility in the solid state, does not present any metallurgical problems, the friction welding of materials which interact among themselves, forming intermetallic phases, is often problematic. Nevertheless, an attempt has been made to apply this technology to join titanium and tungsten pseudoalloy (Densimet D18).

Tungsten pseudoalloy D18 is an alloy produced by the powder-metallurgy method of sintering tungsten grains (forming the matrix (95 wt.%)) with the bonding phase formed by alloy Ni–Fe (3.4 wt.% Ni and 1.6 wt.% Fe) (Fig. 1). This type of material is often used instead of pure tungsten because of the comparative ease of production and machining. It shows similarly high densities as pure tungsten, but it is much easier to machine. Densimet alloys in particular are characterized by excellent strength and ductility.

The advantages of Densimet tungsten alloys include: high density (17.0–18.5 g/cm^3), high X-ray and gamma-ray absorption capacity, good machinability, high Young's modulus, very good mechanical properties and environmental and health friendliness. The typical areas of application are: nuclear radiation shields, engine counterweights, aerospace industry, mechanical engineering, fine mechanical technology, forming and sports [4].

Titanium can be alloyed with, for example, iron, aluminium, vanadium and molybdenum to produce strong lightweight alloys for the aerospace industry (jet engines, missiles, and spacecrafts), the military, industrial processes (chemicals and petrochemicals, desalination plants, pulp and paper), automotive industry, agri-food, medical prostheses, orthopaedic implants, dental and endodontic instruments and files, dental implants, sporting goods, jewellery, mobile phones and others. In these applications one finds titanium–tungsten and titanium–tungsten alloy joints.

2. Experimental

Friction welding was performed using a conventional vertical welder. A diagram of the welding process is shown in Fig. 2a. To protect the joint area from the effect of atmospheric gases, friction welding was conducted in a liquid [1,5–6]. A scheme of the kinds of tested joints is shown in Fig. 2b.

The friction welding parameters for rods dia. 30 mm are shown in Table 1. The joints were evaluated on the basis of metallographic examinations, microhardness measurements and static tensile tests.

3. Results and discussions

3.1. Friction welding of titanium and tungsten

Tungsten and titanium (β) form a system whose solubility is unlimited [7], whereas tungsten is practically insoluble in Ti (α) at a temperature of 500 °C. Because of high fusion temperature of

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0925-8388/$ – see front matter © 2010 Published by Elsevier B.V.
doi:10.1016/j.jallcom.2010.07.062

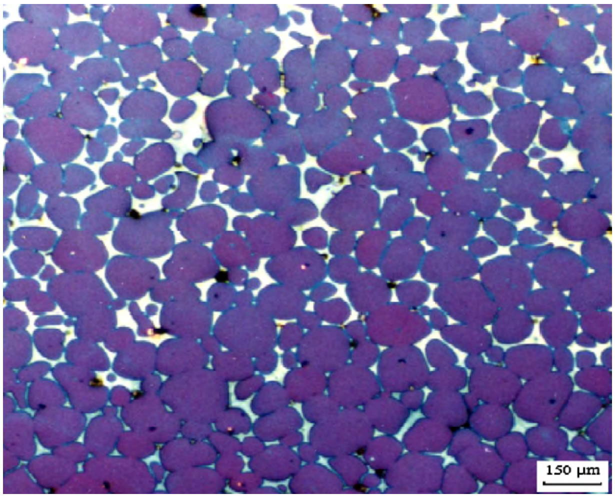

Fig. 1. Microstructure of tungsten pseudoalloy D18.

tungsten and the considerable plasticity of titanium one should use long friction times. A large flash ($s = 30$ mm) occurs on the titanium side (Fig. 3a) and the produced joint has a very narrow diffusion zone (zone A, Fig. 4b) in which the titanium content amounts to about 10 wt.% (Fig. 4). The microhardness of the diffusion zone is 676 $HV_{0.015}$ while that of the base tungsten material is 580 $HV_{0.015}$.

A linear analysis of the distribution of titanium, tungsten in the friction welded joint confirms the existence of the narrow (less than 10 µm) diffusion zone (Fig. 4c).

3.2. *Friction welding of titanium with tungsten pseudoalloy D18*

The friction welding of titanium and tungsten does not present any great difficulties. But the welding of titanium and tungsten pseudoalloy D18 proceeds differently: a heat-affected zone forms on the titanium side, widening in the centre of the specimen. This shape of the heat-affected zone is due to the fact that less heat evolves when welding D18 to titanium than when welding

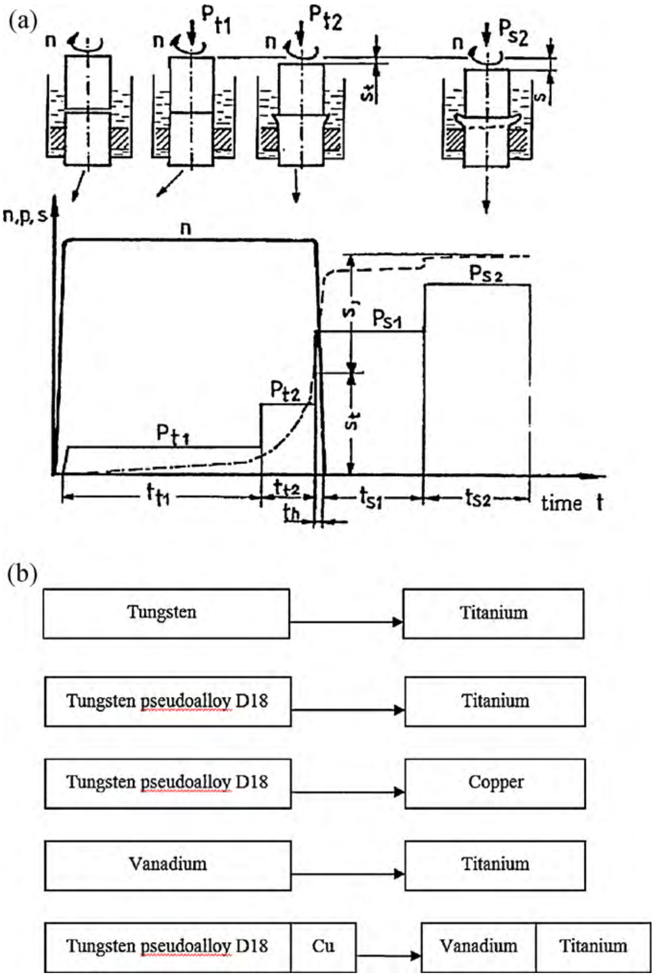

Fig. 2. Scheme of friction welding (a) and kinds of friction welded joints (b).

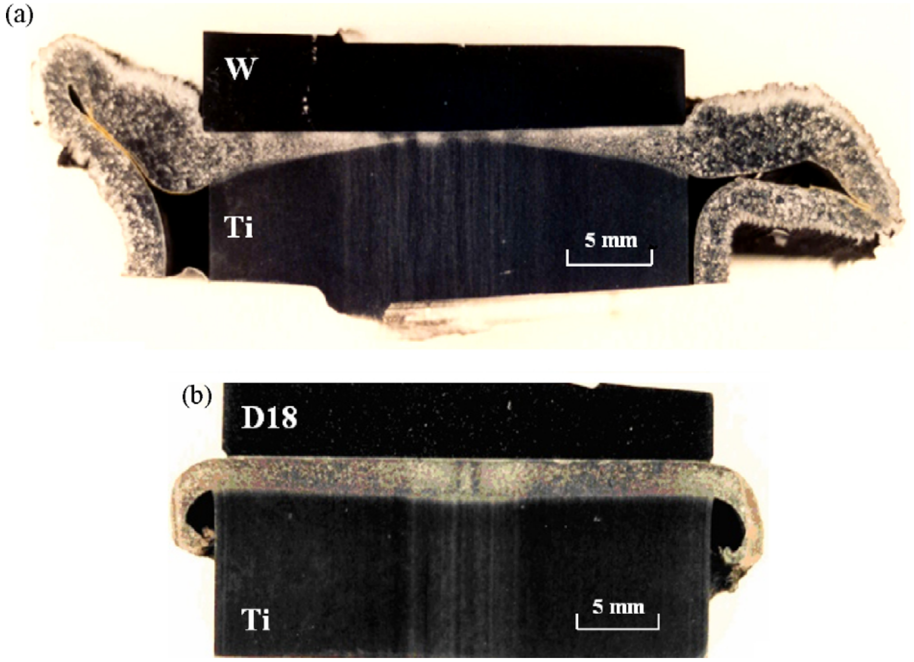

Fig. 3. Titanium–tungsten joint (a) and titanium–tungsten pseudoalloy D18 joint (b).

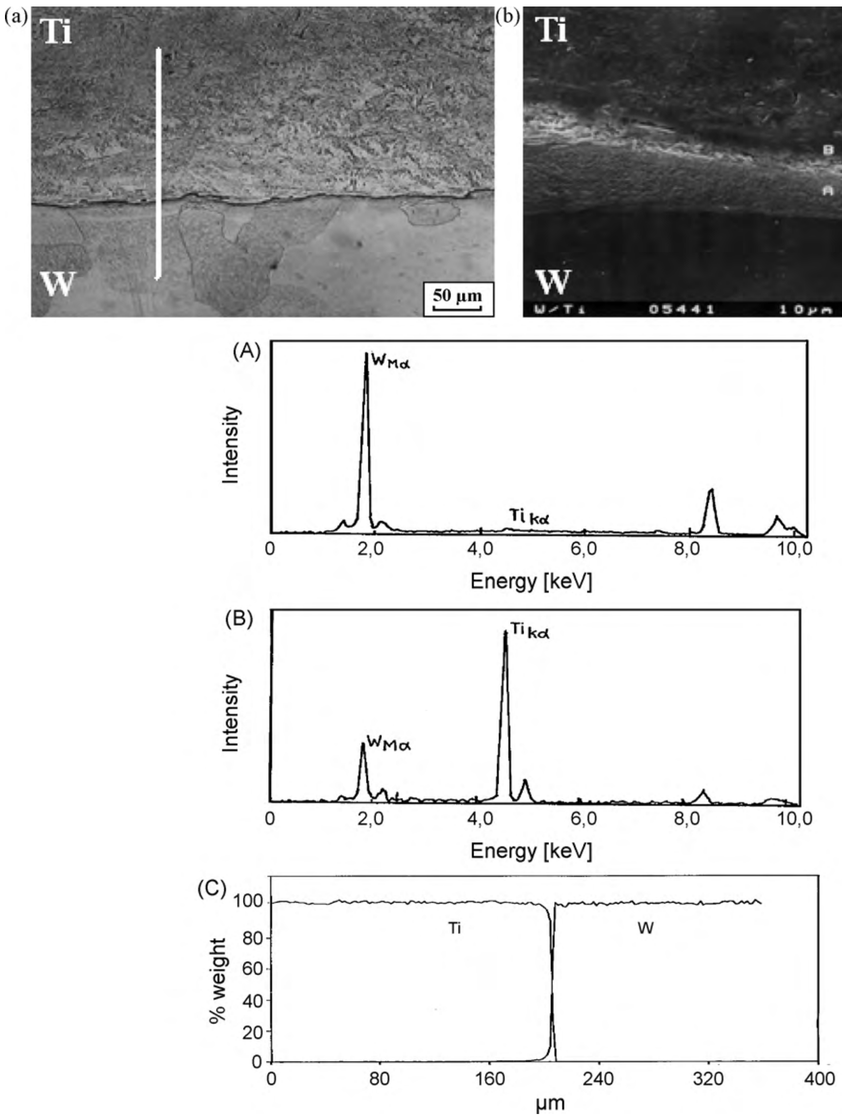

Fig. 4. Microstructure of friction welded titanium–tungsten joint: optical microscopy image (a), scanning microscopy image (b), local EDX analysis of zones A, B and linear titanium and tungsten concentration profiles (c).

Table 1
Friction welding parameters for tested joints.

Material pairs	P_{t1} (N/mm^2)	P_{t2} (N/mm^2)	P_{s1} (N/mm^2)	P_{s2} (N/mm^2)	t_{t1} (s)	t_{t2} (s)	t_{s1} (s)	t_{s2} (s)	s_t (mm	s (mm
Titanium–tungsten	24	30	37	47	3.0	8.5	100.0	100.0	30.0	31.7
Titanium–tungsten pseudoalloy D18*	25	32	38	48	3.0	6.2	100.0	100.0	1.3	1.5
Titanium–vanadium	16	26	40	46	1.3	4.5	1.0	5.0	12.1	12.4
Copper–tungsten pseudoalloy D18	23	49	83	103	20.0	1.9	25.0	25.0	14.4	17.6
Titanium/vanadium-copper/D18	28	65	152	152	3.5	1.4	30.0	30.0	10.4	10.6

$n = 1500\,\text{min}^{-1}$, $^{*}n = 750\,\text{min}^{-1}$, P_{t1} – pressure during the first period of friction, P_{t2} – pressure during the second period of friction, P_{s1} – pressure during the first period of upsetting, P_{s2} – pressure during the second period of upsetting, t_{t1} – duration of the first period of friction, t_{t2} – duration of the second period of friction, t_{s1} – duration of the first period of upsetting, t_{s2} – duration of the second period of upsetting, s_t – contraction during the period of friction, s – total contraction during the whole period of welding.

Table 2
Results of calculations, based on diffraction patterns, of interplanar distances for titanium–tungsten pseudoalloy D18 joint surface.

Titanium side	2.544	2.334	2.272	2.229	2.177				1.724	1.605	1.580
D18 side, d				2.231		2.138	2.066	1.790			1.578
Phase	Ti (2.557)	Ti (2.342)	W(Ti) (2.278)	W (2.24)					Ti (1.726)	W(Ti) (1.61)	W (1.158)

W(Ti) = solid solution of titanium in tungsten with lattice constant $a = 3.222$; structure as that of tungsten—contains about 40 wt.% of titanium; $\delta = \lambda/\sin 2\Theta$.

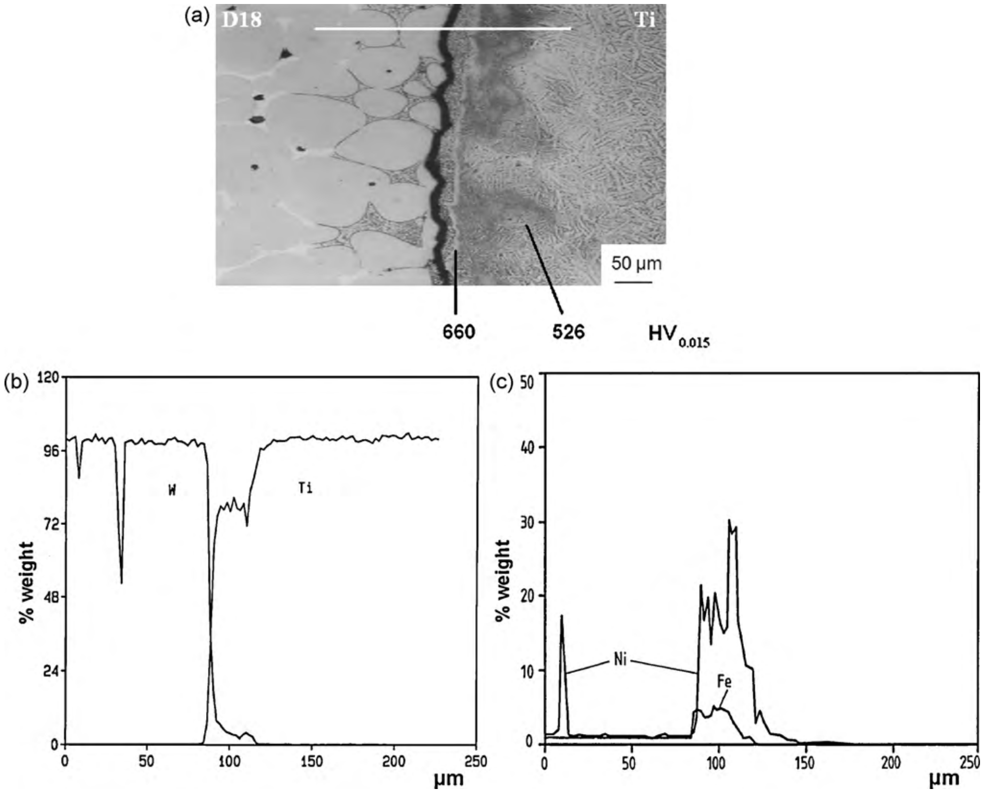

Fig. 5. Friction welded titanium–tungsten pseudoalloy D18 joint: microstructure (a), linear concentration profiles of titanium and tungsten (b) and nickel and iron (c).

tungsten to titanium. In order to obtain defect-free joints, it was necessary to reduce the rate of rotation from the standard 1500 to 750 min^{-1}. In the case of titanium–D18 joints, the specimen contraction was very small (1.5 mm), whereas in titanium–tungsten joints with similar parameters it exceeded 30 mm (Fig. 3).

During welding, a continuous (up to 3 μm wide) zone of intermetallic phases forms on the surface of the joint, widening on the tungsten pseudoalloy D18 side where it penetrates between tungsten grains to a depth of 60 μm (Fig. 5a). Microhardness of the zone is 660 $HV_{0.015}$. The joint is very brittle—it broke when the specimen was dropped from a height of 1 m onto a concrete base. X-ray examinations of titanium–D18 fractures showed the presence of major inclusions of tungsten, a solid solution of titanium in tungsten, titanium and a few minor and difficult to identify inclusions, whose frequency was higher in the specimens with wider zones of intermetallic phases (Table 2). The unidentified inclusions probably originate from the Fe–Ni–W–Ti systems.

The linear distribution of tungsten, titanium and iron in the area of the titanium–tungsten pseudoalloy D18 joint shows that a Ti–Ni–W–Fe phase is produced on the interface (Fig. 5b and c). A local analysis of the hard phase on the interface showed the following material composition: 64% Ti, 26% Ni, 5% W and 5% Fe (all by weight).

3.3. *Titanium–tungsten pseudoalloy D18 joint with copper and vanadium interlayers*

It was decided to use a copper interlayer on the tungsten alloy side and a vanadium interlayer on the titanium side when friction welding titanium and tungsten pseudoalloy D18. Copper does not form intermetallic phases with the bonding phase (Ni and Fe) and does not show any tendency to solubility in tungsten. The use of a copper interlayer alone, as was the case with niobium joints, is impossible here since copper forms several intermetallic phases with titanium. Although direct titanium–copper joints whose strength exceeds that of copper can be produced, special welding parameters (a very high upsetting pressure and a short friction period) are required for this purpose. Moreover, in a titanium–copper joint undergoing an additional thermal cycle, intermetallic phases may appear which will weaken the joint. Therefore a decision was made to introduce interlayers. 35 mm × 35 mm × 5 mm vanadium interlayer platelets were used on the titanium side and the welding parameters listed in Table 1 were adapted. During the solidification of binary titanium–vanadium alloys, a Ti(β)-V solution characterized by unlimited solubility forms from the liquid. As temperature goes down and transformation $Ti(\beta) \rightarrow Ti(\alpha)$ takes place, the Ti(α)–V system components have limited solubility. Below 500 °C, titanium solubility in vanadium is low. In friction welded titanium–vanadium joints, two diffusion zones can be distinguished in the joint plane. The 12 μm wide zone contiguous with vanadium has a hardness of 227 $HV_{0.015}$ (point C in Fig. 6c). It is probably phase β from the Ti–V system. It is adjoined by a narrow $(\alpha+\beta)$ zone with a microhardness of 372 $HV_{0.015}$ (point B in Fig. 6c) and about 8 μm wide zone with a microhardness of 579 $HV_{0.015}$ and a hexagonal structure (point A in Fig. 6c). Local analysis showed 26 wt.% vanadium at the point A, 10 wt.% V at B and 55 wt.% V at C. Concentration of vanadium in the A zone (26 wt.%) and high microhardness (579HV $_{0.015}$) indicate that this is ω phase created in the Ti–V system as a result of supersaturation in the area of the alloys containing 16 to 29 wt.% V [7,8].

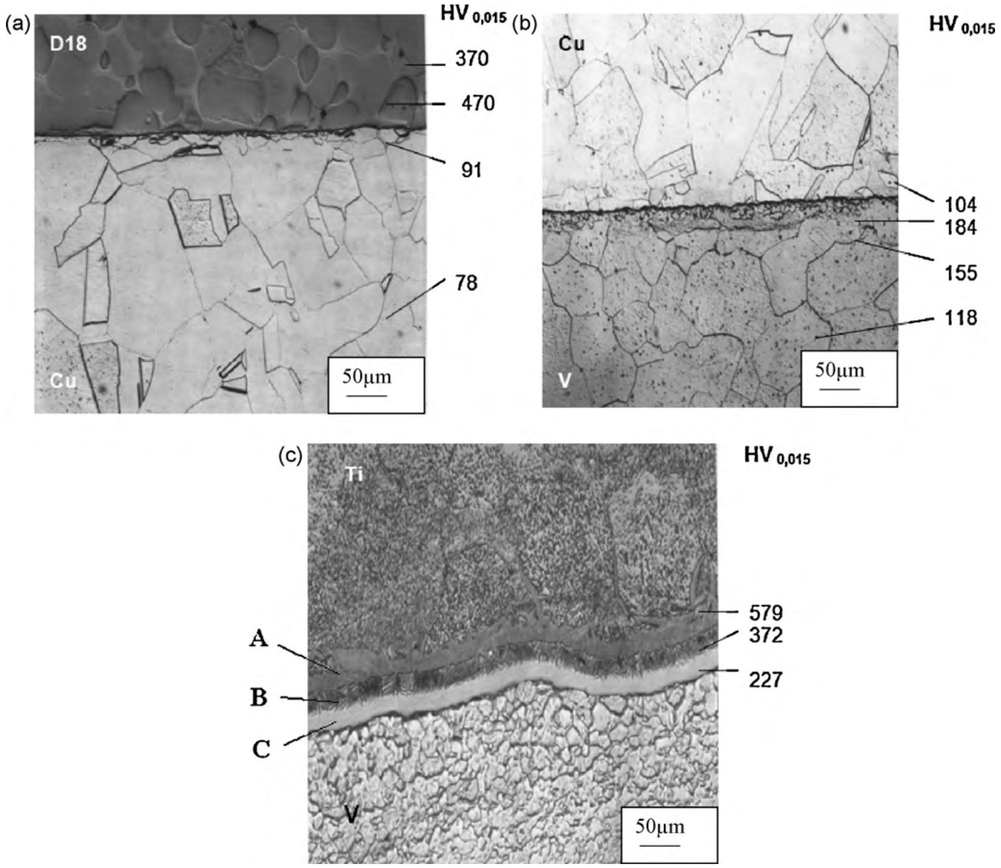

Fig. 6. Microstructures in titanium–tungsten pseudoalloy D18 joints with copper and vanadium interlayers: copper–D18 (a), copper–vanadium (b) and titanium–vanadium (c).

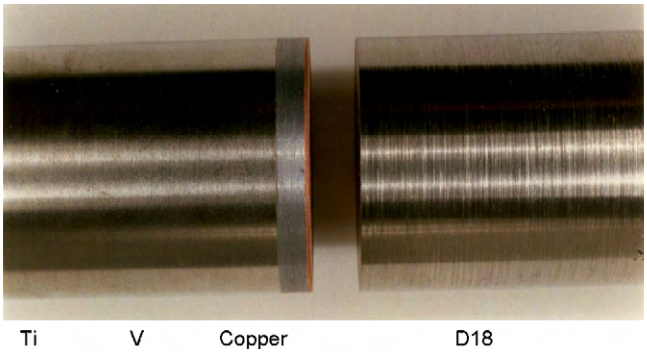

Fig. 7. Titanium–tungsten pseudoalloy D18 after static tensile test.

Titanium–tungsten pseudoalloy D18 joints with copper and vanadium interlayers, as shown in Fig. 2b, were friction welded. After turning the rods to 30 mm, first the tungsten pseudoalloy D18 rod was welded to a 10 mm thick copper interlayer and then the titanium rod was welded to a 5 mm thick vanadium layer. As a result of this procedure, the titanium–tungsten pseudoalloy D18 joint included a 0.8 mm thick copper interlayer and a 4.8 mm thick vanadium layer. The microstructures of the titanium–D18 joint with the interlayers are shown in Fig. 6. The specimen after a static tensile test is shown in Fig. 7. The joints had a maximum strength of 410 N/mm^2. Fractures occurred in the copper layer.

4. Conclusions

1. In the course of the direct friction welding of dissimilar-metal titanium–tungsten pseudoalloy D18 joints, hard intermetallic phases form and they cannot be removed from the whole area of the joint.
2. Through the use of interlayers made of metals which in the solid state do not form intermetallic phases with the friction welded metals one can obtain joints without microcracks.
3. Copper can be used for an interlayer in titanium–tungsten pseudoalloy D18 joints, but an additional vanadium layer is required.

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